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ORIGINAL ARTICLE

Effect of shifting sand burial on soil evaporation and moisture–salt distribution in a hyper-arid desert

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Abstract It is a serious threat for the sustainable protection of the Taklimakan Desert Highway Shelterbelt (TDHS) from shifting sand burial. To explore the effects of shifting sand burial on soil evaporation, salt accumulation and their distribution, Micro-lysimeters were used under sand burial of different thickness (1, 3 and 5 cm) and particle size (<0.063, 0.063–0.20 and 0.20–2.00 mm). The results demonstrated that: (1) soil daily evaporation and accumulative evaporation decreased with the sand burial thickness, and thus evaporative inhibiting efficiency increased. Consequently, the soil water content increased with sand burial thickness (1.48–12.70%) than the control; (2) finer-textured (<0.063 mm) sand burial (0–2 cm depth) promoted soil evaporation and salt accumulation at topsoil, accumulative evaporation increased 5.1 mm and electrical conductivity (EC) of topsoil increased 13.30 dS m^{-1} compared with the control; and (3) while topsoil EC decreased 1.65–6.46 dS m^{-1} with the increase in sand burial thickness, soil EC beneath the sand burial interface showed a reverse trend. We concluded that shifting sand burial has obvious effects on soil water evaporation, salt accumulation and water-salt redistribution, and it could be considered to save water and reduce salt accumulation in arid desert areas like the TDHS with saline irrigation.

Keywords Saline water drip irrigation · Eolian sand deposition · Soil moisture · Soil salinity · Taklimakan Desert

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Introduction

Shifting sand burial is a common natural disaster in drought deserts, especially in the extremely arid Taklimakan Desert in central Eurasia. The Taklimakan Desert, formed about ca. 7 Ma ago in the center of the Tarim Basin (Sun et al. 2009a), is among the driest regions in the world and is called "the sea of death" because of the extremely harsh natural environment. Sand burial significantly influences seed germination (Liu et al. 2011; Zhu et al. 2014), plant growth (Zhang 1996; Brown 1997; Gilbert and Ripley 2008), plant physiology and ecology (Zhang 1996; Xu et al. 2011). Artificial sand burial may inhibit soil evaporation (Diaz et al. 2005; Zhang et al. 2008; Yuan et al. 2008; Liu et al. 2011; Wang et al. 2011), reduce topsoil salt accumulation (Zhang et al. 2008) and decrease soil water infiltration (Mandal et al. 2005). Thus, sand burial may be helpful to maintain crop yield and soil quality because soil moisture and salt accumulation are two important limiting factors for crop production in most arid regions.

The Taklimakan Desert Highway Shelterbelt (TDHS) transects the Taklimakan Desert from south to north and borders a section of the highway 436 km long and 72–78 m wide. Given the extreme paucity of freshwater resources, all plants in the TDHS are drip irrigated with local groundwater of high salinity (2.58–29.70 g L^{-1}) (Xu et al. 2006; Han et al. 2012; Zhang et al. 2013). The TDHS successfully stabilized the shifting sand (Han et al. 2003; Lei et al. 2008), but the drip irrigation tubes were buried by the accumulated shifting sand because they were placed on the land surface during construction of the TDHS. High potential evaporation and drip irrigation with highly saline groundwater normally lead to loss of irrigation water and accumulation of soluble salts in the shallow soils in the TDHS (Zhang et al. 2013). Therefore, water limitation and salt stress on the TDHS plants are two of most critical factors that influence the stability of the TDHS (Zhou et al. 2006; Zhang et al. 2016).

Previous studies mainly focused on the effects of artificial sand burial in reducing soil water evaporation and increasing crop yields in farmland. The reduction in accumulative evaporation varies with the thickness and grain size of stone and organic mulches (Kamar 1994; Diaz et al. 2005). Accumulative evaporation declined with mulch thickness because the mulch retards the capillary movement of water to the soil surface, but mulch grain size has no obvious impact (Diaz et al. 2005; Xu et al. 2011). Few studies have investigated the dynamics of soil moisture and salt accumulation under shifting sand burial (Sun et al. 2009b). Limited water resources are extremely important in arid ecosystems, so it is crucial to study the efficient use of soil and water resources in arid shifting deserts, the effects of shifting sand burial on soil water evaporation and salt dynamics, desertification controls associated with the sand burial mechanisms and therefore the sustainable utilization of local water resources.

In this study, micro-lysimeters (MLS) were used to monitor the dynamics of soil moisture and salt accumulation under sand burial with different thicknesses and with different grain sizes. The objectives were (1) to clarify the influence of sand burial thickness and grain size on soil evaporation and moisture–salt distribution, and (2) to explore a suitable method for water conservation and reduction in salt accumulation. The findings may provide a theoretical basis and technical support for maintenance and management of the TDHS.

Study site

The study was conducted at the Taklimakan Desert Research Station, Chinese Academy of Sciences (39°01′N, 83°36′E, 1 100 m a.s.l.; Fig. 1), which is located in the hinterland of the Taklimakan Desert, in August 2013. The annual mean air temperature of the study area is 12.4 °C, with the coldest monthly mean temperature of −8.1 °C in December and the warmest monthly mean temperature of 28.2 °C in July. Average annual precipitation is 24.6 mm, but annual potential evaporation is up to 3639 mm and average annual relative humidity is 29.4%. Thus, the region is considered to experience hyper-arid conditions. The average annual wind speed is 2.5 m s^{-1} and the maximum wind speed is 20.0 m s^{-1}. Sand-shifting winds occur on more than 130 days per annum.

The ground landscapes are mainly mobile dunes and large complex dune chains (Fig. 2), which have been described previously by Li et al. (2008) and Liu et al. (2012). The natural vegetation of the study area is extremely sparse except for a few extremely drought-resistant shrubs (e.g., *Tamarix taklamakanensis* M.T. Liu and *Calligonum taklimakanensis* B.R. Pan & G.M. Shen) growing in some areas with shallow groundwater in inter-dunes (Fig. 2). The soil type is Xeric Quartzipsamments, derived from shifting eolian sand (Soil Survey Staff 2014). The soil texture is uniform and distinct soil horizons are absent. The soil has poor water-holding capacity and contains few nutrients (Jin et al. 2008). The salt content is 1.26–1.63 g kg^{-1}, which mainly comprises Cl^-, SO_4^{2-}, K^+ and Na^+ ions (Zhang et al. 2013), and the pH is 8–9. The basic properties of the soil were determined by traditional methods (Table 1, Zhang et al. 2013). The groundwater level is shallow (3–5 m depth) in the inter-dune areas, which are characterized by salinity of 4.0–4.8 g L^{-1} with ionic contents primarily composed of Cl^-, SO_4^{2-}, Na^+ and K^+ (Table 2).

The main plant species in the TDHS are *Calligonum arborescens, Tamarix ramosissima* and *Haloxylon ammodendron*, which are highly drought and salt tolerant and show strong wind-breaking and sand-stabilization properties (Zhang et al. 2009). All plants are drip irrigated with local groundwater of high salinity (2.82–29.87 g L^{-1}). The irrigation interval is 15 days in March, April, May, September and October, and 10 days in June, July and August. The irrigation rate is 30 L $tree^{-1}$ per application. The irrigation schedule was determined by Xu et al. (2006) based on the dual K_c method (Allen et al. 1998) after field experiments conducted for several years and is applied to the entire TDHS.

Materials and methods

Experimental design

Micro-lysimeters (MLS) were composed of two cylindrical PVC tubes of different diameters (inner and outer diameters 10 and 12 cm, respectively) and of height 26 cm (Plauborg 1995; Yan et al. 2012), which were operated using the following procedures. The basic properties of the experimental soils and irrigation water are presented in Tables 1 and 2. First, an area (5 m × 5 m) of shifting sandy land was delimited and sufficiently furrow-irrigated with saline water (4.04 g L^{-1}) and then covered with

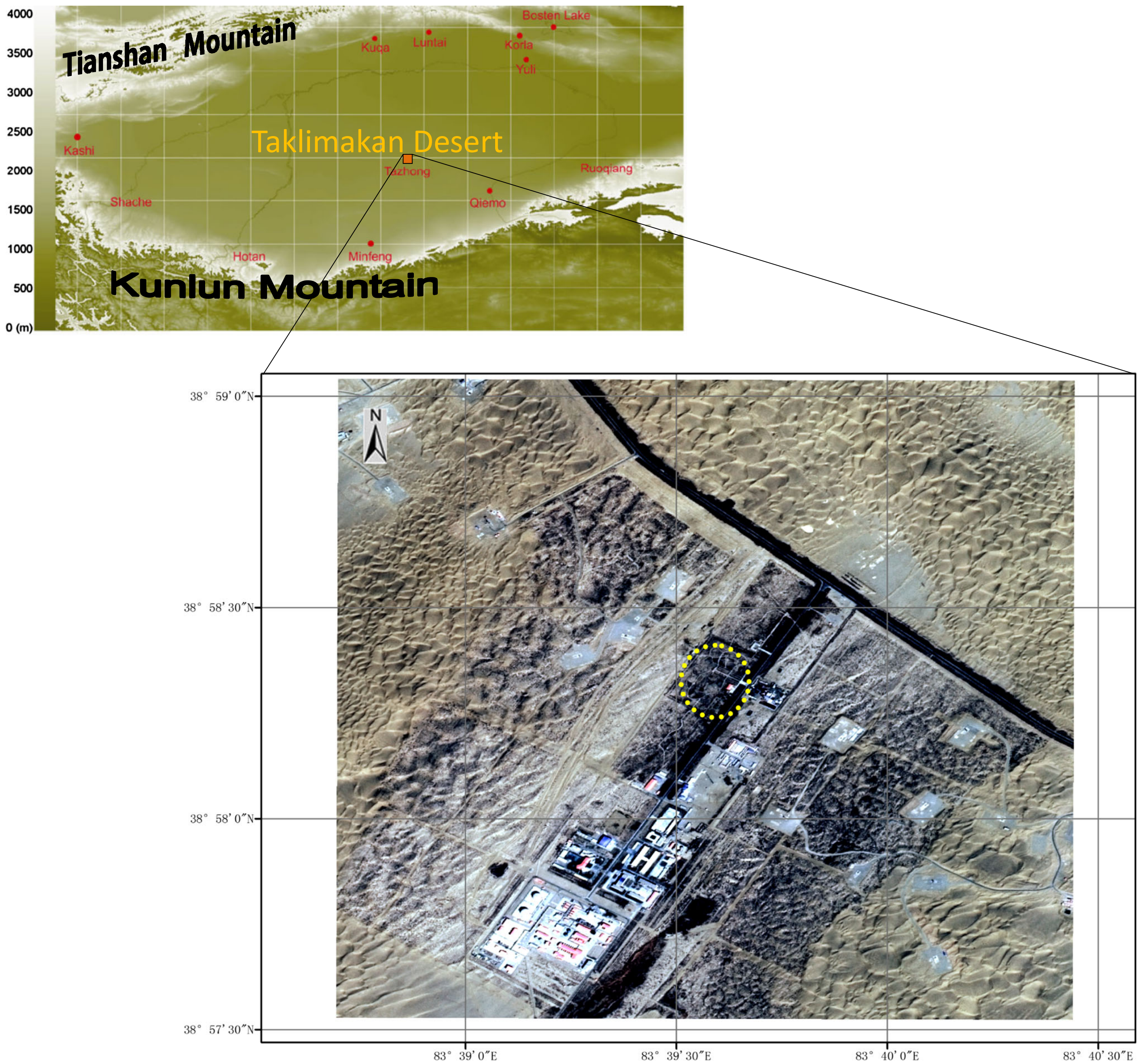

Fig. 1 Topographic map of the Taklimakan Desert, location and landscape of the study site. *Yellow line circles* the location of Taklimakan Desert Research Station (*upper map* is modified from Liu et al. 2012)

plastic film for 12 h. Second, the inner tubes of the MLS were pressed vertically into the irrigated soil to 20 cm depth to obtain soil columns, and then the soil at the bottom of the tube was cut cleanly with a knife and sealed with a rubber belt. Under this condition, the soil moisture content was 26.7%, which was regarded as the saturated value. Third, the surface of the soil columns was covered with natural shifting sand (Fig. 3), which was applied as two treatments with three levels (five replicates per level). One treatment comprised three thicknesses of sand burial: 1 cm (H_1), 3 cm (H_3) or 5 cm (H_5); the second treatment consisted of different sand particle sizes applied to the same thickness (2 cm): <0.063 mm (GS_1), 0.063–0.20 mm (GS_2) and 0.20–2.00 mm (GS_3). The three particle sizes were obtained by sifting sand through sieves of different mesh sizes. Five MLS which were not subjected to sand burial were considered to be controls.

All outer tubes were buried in the soil, with the top of the tube parallel to the soil surface, in the middle between two rows of shelterbelt plant. The prepared inner tubes containing the soil columns were placed in the buried outer tubes. The shelterbelt plants at the experimental site were planted in the spring of 2003 with spacing of 2 m between rows and 1 m between individual plants within the same row. The shelterbelt was planted about 10 years ago, and the coverage is up to 100%. The inner tubes were weighed

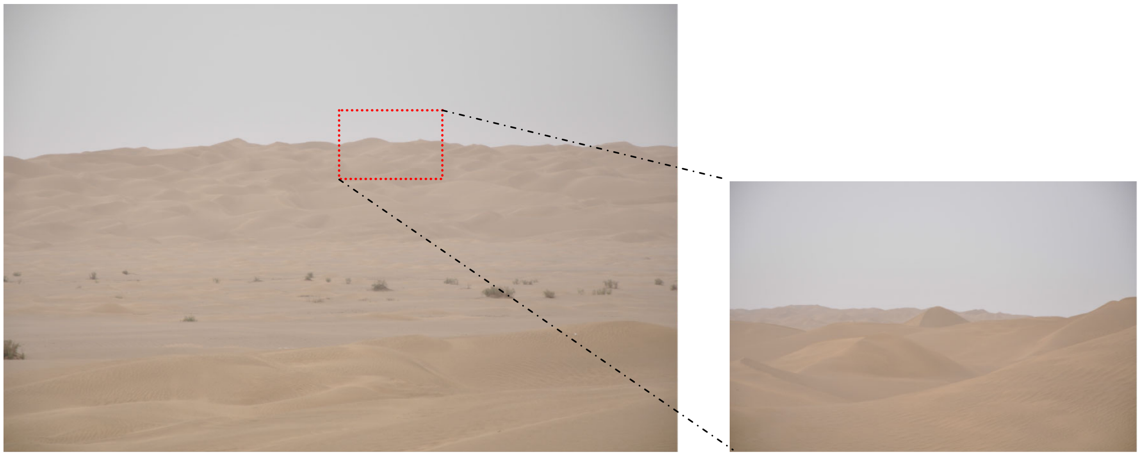

Fig. 2 Ground landscapes and natural vegetation at inter-dunes of the study site (photos were taken by Jianguo Zhang in August 2013)

Table 1 Physical and chemical properties of shifting sandy soil at the study area

pH (1:5)	Electrical conductivity (dS m^{-1})	Total salt content (g kg^{-1})	Bulk density (g cm^{-3})	Particle composition (%)			
				Clay (<0.002 mm)	Silt (0.002–0.02 mm)	Fine sand (0.02–0.2 mm)	Coarse sand (0.2–2 mm)
8.26	0.437	1.31	1.49	0.27	12.35	82.83	4.54

Table 2 Chemical properties of the drip irrigation groundwater at the study site

pH	Electrical conductivity (dS m^{-1})	Salinity (g L^{-1})	Ions composition (g L^{-1})					
			HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+ and Na^+
8.13	6.06	4.04	0.08	1.50	1.01	0.11	0.15	1.07

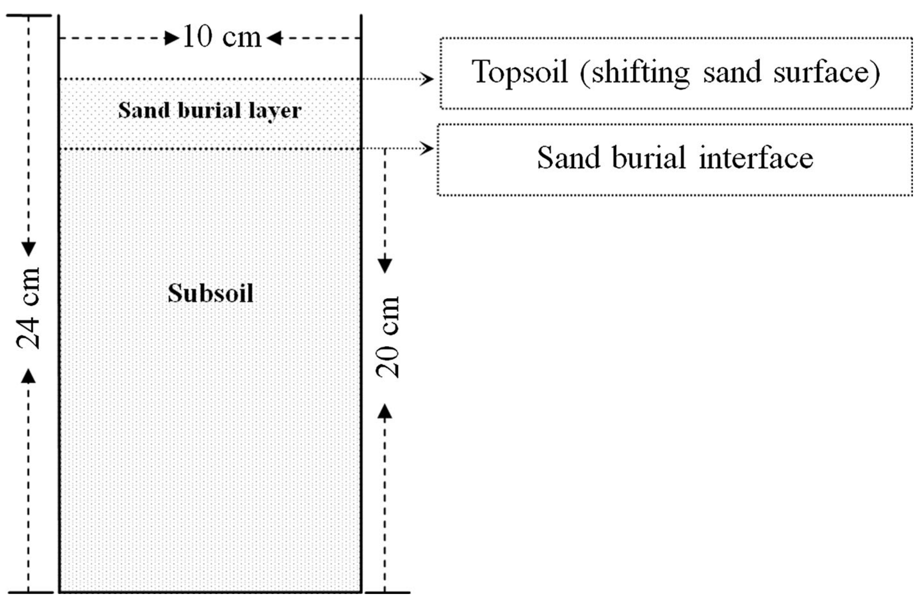

Fig. 3 Schematic diagram of the soil

daily at 20:00 for 15 days using an electronic balance (range 3600 g, precision 0.01 g; LP-6200S, Sartorius Group, Göttingen, Sachsen, Germany). After the final weight measurement, the soils in the surface layer (0.5 cm depth) and soil beneath the sand burial interface were sampled and divided into two portions. One portion was used to determine the final moisture content by mass, and the other portion was air-dried to measure EC with a temperature–conductivity meter (ZKNT-SY-3, Centrwin Technology Co., Ltd., Beijing, China) based on extracts of 1 part soil to 5 parts water by weight (Zhang et al. 2013; Chen et al. 2015).

Data analysis

To measure evaporation, three different statistical indices of daily evaporation (ED), accumulative evaporation (EA) and evaporation inhibition efficiency for sand burial (*I*) were calculated as follows (Zhang et al. 2010, 2013):

$$\mathrm{ED}_i = 10 \times (\mathrm{WE}_i - \mathrm{WE}_{i-1})/A \tag{1}$$

$$\mathrm{EA}_i = 10 \times (\mathrm{WE}_0 - \mathrm{WE}_i)/A = \sum \mathrm{ED}_i \tag{2}$$

$$I = 100\,\% \times (\mathrm{EA}_{0i} - \mathrm{EA}_i)/\mathrm{EA}_{0i} \tag{3}$$

where ED_i (mm) is the daily evaporation on the *i*th day, WE_i (g) is the weight on the *i*th day, EA_i (mm) is the accumulative evaporation on the *i*th day, WE_0 (g) is the initial weight of the inner MLS containing the soil column, A (cm^2) is the sectional area of the inner MLS, I (%) is the evaporation inhibition efficiency of sand burial and EA_{0i} (mm) is the accumulative evaporation of the control on the *i*th day. Evaporation inhibition efficiency (*I*) is a measure of the degree of inhibition of soil evaporation for one or more measurements (or factors) (Zhang et al. 2010).

The experimental design was a randomized complete block, and the data were analyzed by means of a single-factor analysis of variance (ANOVA) with SPSS version 13.0 (SPSS, Inc., Chicago, Il, USA). A one-way ANOVA was conducted to examine the effects of sand burial on moisture evaporation and moisture–salt distribution. Multiple pair-wise comparisons were made using Tukey's adjustment. All results are reported at $\alpha = 0.05$ level of significance.

Results and discussion

Effects of thickness of sand burial on soil evaporation

Daily evaporation (ED) decreased with thickness of sand burial (Fig. 4). From the start of the experiment to the day 7, ED for each of the three thicknesses was considerably less than that of the control. In addition, ED of the control decreased much more rapidly than that of burial treatments, which was associated with the rapid reduction in soil moisture content of the control. Consequently, ED of the control was less than that of each sand burial treatment on the 15th day.

After irrigation, soil EA logarithmically increased with duration of sand burial of different thicknesses and all for each burial treatment was much less than that of control (Fig. 5). This finding indicated that sand burial of different thicknesses can significantly inhibit soil moisture evaporation. This result is similar to the findings of other authors (Kamar 1994; van Wesemael et al. 1996; Diaz et al. 2005) who reported reduced evaporative loss of moisture from gravel–mulched soils. Following shifting sand burial in the present study, the reduction in soil moisture evaporation was less marked, mainly because of the difference in grain size. The grain size of shifting sand is much smaller than that of gravel; hence, the capillarity action is stronger. Significant differences in final soil EA between burial thicknesses and the control were observed (Table 3; $p < 0.05$). These results demonstrated that sand burial of different thicknesses can significantly reduce soil EA, which is favorable for soil moisture conservation and plant growth in the TDHS.

Under the same initial soil water content, final *I* (day 15) increased with sand burial thickness (Table 3). The lowest value of *I* (13.99%) was observed with sand burial of 1 cm thickness, and the highest value (78.30%) was observed with burial of 5 cm thickness. The value of *I* decreased linearly with time (Fig. 6). *I* was highest on day 1 when the soil moisture content was highest and declined with reduction in moisture content. These results indicated that sand burial of different thickness effectively inhibited soil moisture evaporation and therefore preserved soil water.

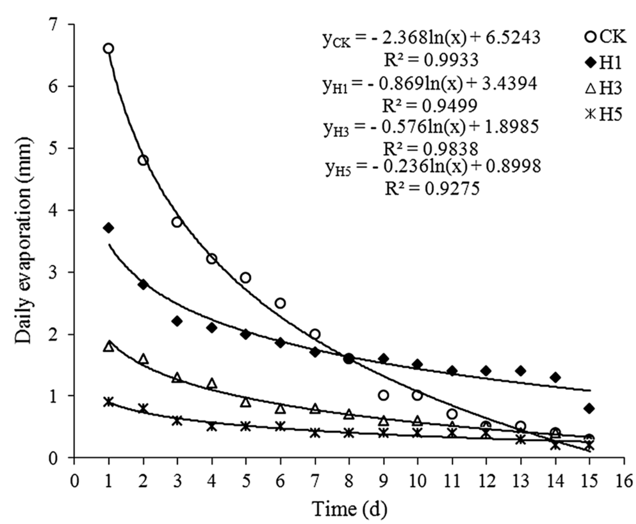

Fig. 4 Dynamics of daily evaporation during one irrigation cycle under sand burial with different thicknesses. H_1, H_3, H_5, *CK*: sand burial thickness of 1, 3, 5 cm and control, respectively

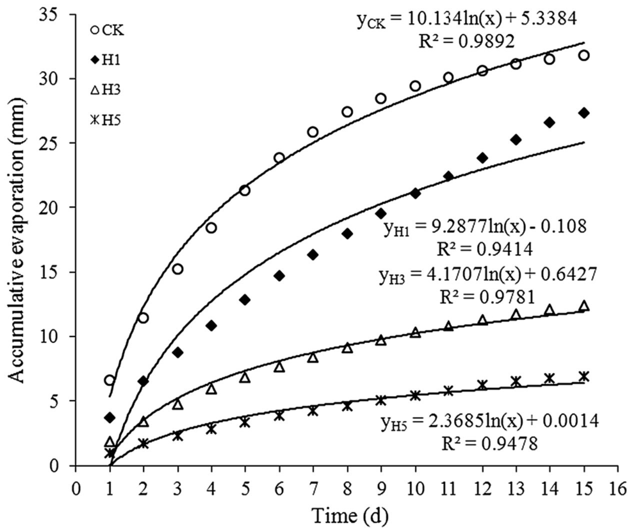

Fig. 5 Dynamics of accumulative evaporation under sand burial with different thicknesses. H_1, H_3, H_5, *CK*: sand burial thickness of 1, 3, 5 cm and control, respectively

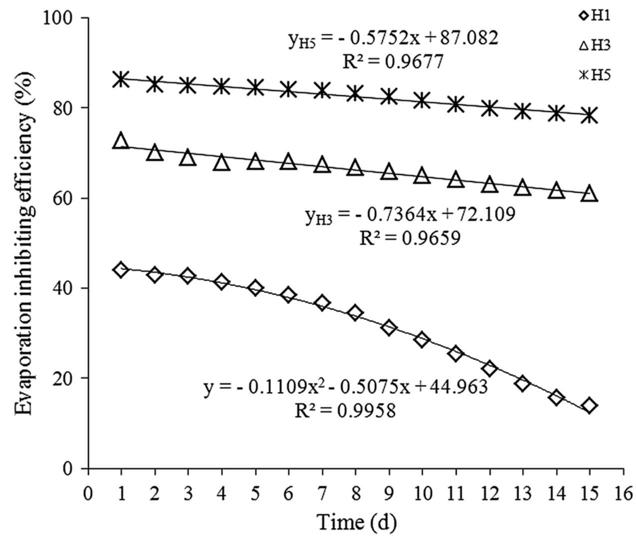

Fig. 6 Dynamics of evaporation inhibition efficiency under sand burial with different thicknesses. H_1, H_3, H_5, *CK*: sand burial thickness of 1, 3, 5 cm and control, respectively

The mechanism of evaporation inhibition under sand burial of different thicknesses was considered as follows. First, sand burial cuts off the capillary movement of soil water in the macro-pores (Diaz et al. 2005). Consequently, soil water must diffuse through the macro-pores among the sand grains into the atmosphere in the form of vapor (Shahraeeni et al. 2012). The larger the sand burial thickness, the longer the distance through which soil water vapor diffuses. In addition, sand burial protects damp irrigated soil from direct exposure to solar radiation. Therefore, evaporation from the soil surface is dramatically reduced owing to decrease in heat energy absorption. Furthermore, the routes for vapor diffusion among the wet soil particles to the atmosphere are lengthened dramatically with increasing thickness of sand burial. Thus, evaporation of soil moisture was significantly inhibited, and higher quantities of water can be conserved in the soil.

Effects of sand grain size on soil moisture evaporation

The dynamics of ED as influenced by sand grain under the same burial thickness of 2 cm are shown in Fig. 7. The ED of GS_1 and the control decreased more rapidly than that of GS_2 and GS_3, which showed the same trend. The ED of GS_1 was always higher than that of the control. The ED of GS_2 and GS_3 showed the same trend, and the ED of GS_2 was always slightly higher than that of GS_3. The initial soil moisture content in the MLS was uniform; hence, higher ED leads to less available evaporable water remaining in the soil. Thus, the ED of GS_1 and the control was even lower than that of GS_2 after day 11 and lower than that of GS_3 after day 14.

Soil EA logarithmically increased under burial with sand of different grain sizes (Fig. 8). The EA values of GS_1 were always the highest, whereas those of GS_2 and GS_3 were much lower than those of control. This result differed from the findings of other authors (e.g., Diaz et al. 2005), who observed that EA was significantly inhibited but showed no obvious difference with grain size, probably because different grain sizes and different thicknesses were used in the experiments. Following shifting sand burial in the present study, the reduction in EA was less marked, probably because of grain size. From this result, we deduce that burial with finer-grained particles can increase soil moisture evaporation. On the contrary, burial with coarser-

Table 3 Significance test on difference of accumulative evaporation (EA) and final evaporation inhibition efficiency (*I*) of different treatments

Evaporative indicator	Treatment						
	Control	H_1	H_3	H_5	GS_1	GS_2	GS_3
EA (mm)	31.8 b	27.35 c	12.40 e	6.91 f	36.90 a	17.27 d	12.05 e
Final *I* (%)	–	13.99 d	61.00 c	78.30 a	−16.19 e	47.20 c	63.15 b

H_1, H_3, H_5, CK: sand burial thickness of 1, 3, 5 cm and control, respectively

Different letters indicate significant difference at a 0.05 level grained sand particles decreases soil moisture evaporation. The differences in final soil EA between the grain size treatments and the control were significant (Table 3; $p < 0.05$). These results demonstrated that burial by sand of different grain sizes has an important influence on soil moisture evaporation and ultimately will affect plant growth in the TDHS.

Under the same initial soil moisture content and the same sand burial thickness of 2 cm, I decreased with moisture reduction from the day 1 to the day 15 (Fig. 9). The value of I was highest on day 1 when soil moisture was close to saturation, and the difference in I between GS_2 and GS_3 increased with time. Final I (day 15) increased with increasing grain size (Table 3). The lowest final I (−16.19%) was observed under burial with clay particles (GS_1; grain size <0.063 mm). Thus, burial with clay particles to 2 cm thickness accelerated soil moisture evaporation, whereas coarser-grained particles inhibited soil water evaporation. Soils of different grain size show different porous properties, which have a strong influence on soil moisture evaporation. The suction head of the capillary was inversely proportional to the radius of soil particles (Kosugi 1996), because GS_1 had the finest soil particles with the largest amount of capillary pores and the strongest soil water suction, which were advantageous for moisture evaporation. Thus, the ED of GS_1 was highest in the early stages of the experiment. With the growth of the shelterbelt plants, increasing quantities of fine particles and dust accumulated in the shelterbelt (Jia et al. 2007) will change the soil capillary conditions and ultimately improve soil moisture evaporation. It is assumed that burial thickness with fine grains should not exceed the height of capillary water rise, otherwise fine-grained particles will inhibit soil moisture evaporation.

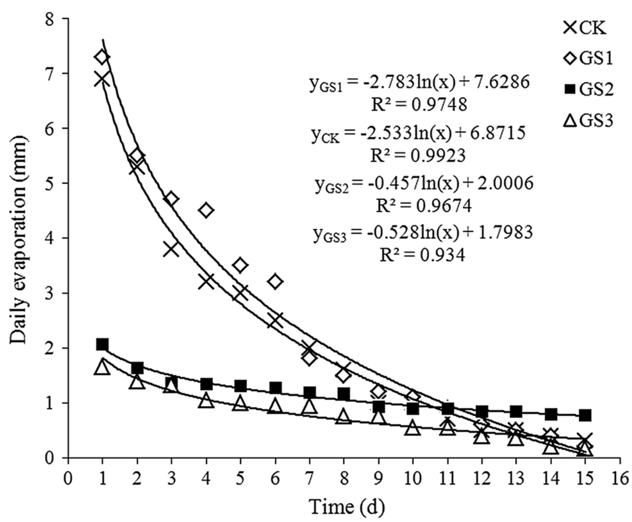

Fig. 7 Dynamics of daily evaporation under sand burial with different grain sizes. *GS_1, GS_2, GS_3, CK*: grain size of sand burial of <0.063, 0.063–0.20, 0.20–2.00 mm and control, respectively

Effects of sand burial on soil moisture and salt redistribution

Soluble salts move with soil water, and thus changes in EA inevitably influence redistribution of soil moisture and salt. Table 4 shows the redistribution of soil moisture and salt under different sand burial treatments after evaporation for 15 days. Final moisture content increased, but salt content in the topsoil (0–0.5 cm depth) decreased with sand burial

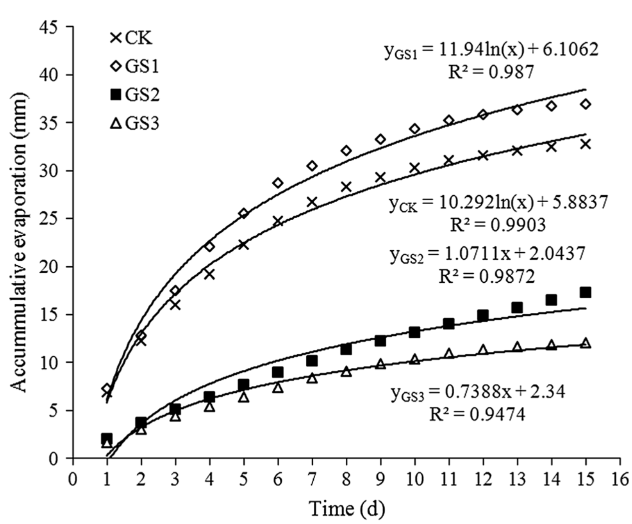

Fig. 8 Dynamics of accumulative evaporation under sand burial with different grain sizes. GS_1, GS_2, GS_3, CK: Grain size of sand burial of <0.063, 0.063–0.20, 0.20–2.00 mm and control, respectively

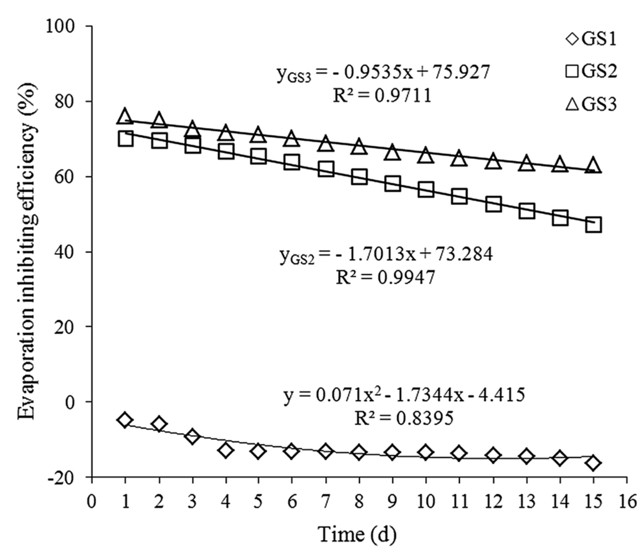

Fig. 9 Dynamics of evaporation inhibition efficiency under sand burial with different grain sizes. *GS_1, GS_2, GS_3, CK*: grain size of sand burial of <0.063, 0.063–0.20, 0.20–2.00 mm and control, respectively

thickness. The moisture contents of H_1, H_3 and H_5 were significantly higher, whereas topsoil EC was significantly lower than those of the control. The salt contents of subsoils were considerably less than those of the topsoil and increased with sand burial thickness, whereas subsoil EC showed no difference with sand burial thickness (Table 4; $p < 0.05$). Thus, shifting sand burial had no influence on redistribution of subsoil salt.

Compared with the control, final moisture content was the lowest for GS_1, but much higher for GS_2 and GS_3 ($p < 0.05$). The topsoil salt content of GS_1 was much higher, whereas those of GS_2 and GS_3 were much lower, compared with that of the control; the differences among the three treatments and the control were significant (Table 4; $p < 0.05$). However, the salt content of the subsoil was considerably lower than that of the topsoil, and the differences between the three treatments and the control were not significant. This is mainly because burial with fine-textured sand accelerated moisture evaporation, which led to higher rates of evaporation and salt accumulation in the topsoil and therefore decreased salt content in the subsoil.

The present results indicated that salt accumulation in the topsoil was influenced by sand burial, but that of deeper soils was less influenced by burial. Soluble salts accumulate at the soil surface less readily with deeper sand burial. Soil moisture evaporation is mainly determined by weather conditions and soil characteristics (Diaz et al. 2005). Soil moisture content of the control was saturated at the start of the experiment, and water rose under the effect of soil capillarity, which formed a stable dehydration process. Subsequently, soil water passed through the dry sand layer of different thickness, and water readily passed through either a shallow sand layer or large sand grains. With continued evaporation, surface soil moisture decreased and formed dry sand layers, and soil moisture loss gradually changed from capillary-dominant to water vapor diffusion processes (Liu et al. 2011). Generally, finer-textured sand forms larger capillaries, which accelerate soil evaporation and upward movement of soluble salts and therefore decrease contents of moisture and salt that remain beneath the interface with the sand burial layer. A dry sand layer forms after shifting sand burial or moisture evaporation for a certain period. Subsequently, moisture from lower soil depths passes through the dry sand layer, mainly via vapor diffusion, which decreases soil moisture evaporation (Shahraeeni et al. 2012). Finally, soil moisture content decreases with continuous evaporation, and the dry sand layer blocks downward transfer of surface heat energy. Therefore, shifting sand burial markedly inhibits the soil moisture vapor flow. Furthermore, this may result in less salt accumulation in the topsoil as a result of decreased evaporation, which should be beneficial for plant growth.

It is noted that MLS experiments show differences from field investigations (Plauborg 1995); therefore, field-based experiments are planned in the future. At the Taklimakan Desert Research Station, local weather data are accessible, which could be combined with the present results and data on water consumption by the shelterbelt plants to construct a model for estimation of the decrease in soil water evaporation rate as a function of sand burial thickness and grain size. The model could estimate local reference evapotranspiration, which could be used for optimization of irrigation schedules and water management (Allen et al. 2005a, b; Mutziger et al. 2005), based on the burial thickness and grain size of shifting sand and water consumption of the shelterbelt plants (Xu et al. 2008).

Conclusions

Shifting sand burial is a serious natural problem in the Taklimakan Desert and, together with drought and salt stress, represents major limiting factors for TDHS plant growth. We simulated the evaporation process of saline irrigated soils under shifting sand burial with different thicknesses (1, 3 and 5 cm) and with different particle sizes (<0.063, 0.063–0.20 and 0.20–2.00 mm) in the hinterland of the Taklimakan Desert. The results demonstrated that sand burial of different thicknesses reduced soil water evaporation and topsoil salt accumulation, and evaporation inhibition efficiency increased with burial thickness. Burial with coarse particles (0.063–0.20 and 0.20–2.00 mm) inhibited soil water evaporation, whereas fine particles (GS <0.063 mm) accelerated soil moisture evaporation and topsoil salt accumulation. Shifting sand burial with

Table 4 Significance test on difference of final moisture content, electrical conductivity (EC) of topsoil and subsoil of different treatments

Soil water–salt indicator	Treatment						
	CK	H_1	H_3	H_5	GS_1	GS_2	GS_3
Final moisture content (%)	2.15 f	3.63 e	10.32 d	14.85 b	1.76 g	11.23 c	15.99 a
EC of topsoil (dS m^{-1})	7.33 b	5.68 c	2.12 e	0.87 g	20.63 a	4.07 d	1.58 f
EC of subsoil (dS m^{-1})	0.16 a	0.21 a	0.49 a	0.81 a	0.16 a	0.42 a	0.58 a

Different letters indicated significant difference at a 0.05 level different thicknesses and with different grain sizes also significantly influenced soil moisture and salt redistribution. The presented findings will assist with shelterbelt construction and sustainable management, and with soil and water conservation and utilization in shifting desert regions.

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